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MONOLITHIC BACKBONE RAILGUN

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Monolithic Backbone Railgun

Eric L. Kathe, John A. Mallick

Abstract -- The vast majority of all operational railguns in the world employ a metallic containment housing. Often composed of thousands of precision sheet metal laminates to prevent induced eddy currents, the launchers are labor intensive to build. The backbone railgun provides a monolithic metallic containment structure. Induced eddy currents are inhibited by the introduction of a large number of slits along the length of the launcher that achieve an effect analogous to traditional laminates. It is anticipated that the machining of slits from a monolithic launcher will lend itself to factory automation far more so than assembling a full length launcher from thousands of individual metal laminates. The principal advantages are 1) elimination of stack-up tolerances, 2) producibility, and 3) stiffness. This paper will refine the concept and include an assessment of its ability to achieve magnetic transparency relative to traditional designs.

Index Terms -- railgun, structural containment, eddy current.

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INTRODUCTION

The firing of a railgun requires large current pulses that generate very large magnetic fields and subsequent Lorentz loads. In analogy with pressure in powder gun launchers, the forces that act to propel the armature projectile through the railgun launcher concurrently apply substantial rail repulsion loads. Thus, the railgun housing must provide robust structure to contain the rails. In addition to this mechanical demand, the housing itself must not support the formation of performance-robbing eddy currents. This requirement, herein referred to as magnetic transparency, hinders the application of conductive metallic housing materials.

Railgun containment housings may be achieved using conductive materials if the structure is specially fabricated to inhibit the formation of eddy currents. The use of thin metallic laminations enables the diffusion of the transverse magnetic field in microseconds [1]. The seminal contribution of the backbone railgun is that the incorporation of side slits along the length of a monolithic conductive launch tube may also achieve magnetic transparency. The remaining axial structure of the tube is analogous to a skeletal backbone and sternum, connected by laminate ribs. Considering symmetric designs for the remainder of this paper, the common width of the backbone and sternum may be termed the backbone web. A basic backbone railgun is depicted in Fig. 1.

BACKGROUND

Most operational railguns in the world may be categorized as lab launchers. These systems are only intended to determine concept feasibility and develop technical data. Most lab launchers employ a split stacked metallic laminate construction as described by Bauer and Newman [2]. This construction is typified by the IAT Medium Caliber Launcher (MCL) [3]. This split construction enables swift and inexpensive removal, inspection, and replacement of the railgun core consisting of the rails separated by sidewall insulators and sheathed within a backing insulator. Efforts have been undertaken to advance the state of the art in launcher technology beyond lab launchers with credible steps towards weaponization. Not to be misunderstood as weapon prototypes, these excursions have made limited efforts to demonstrate the feasibility of technical solutions

to the obvious drawbacks of lab launchers. Although a litany of objectives could be listed and exceptions made for unusual designs, we will highlight six basic housing requirements:

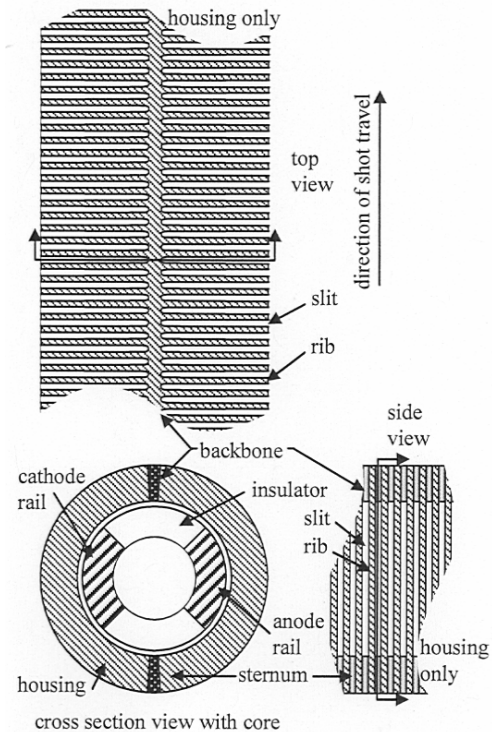


Fig. 1 Basic Backbone Railgun Housing.

Table I. Launcher Housing Requirements

| | |
|-----------------|---|
| Efficiency | Maximize inductance gradient to minimize power requirements and Ohmic heating. |
| Weight | The overall weight of the launcher should be minimized. |
| Cantilever | The ability of the launcher to support its own weight and provide sufficient beam flexural stiffness to be effectively slewed and pointed as a weapon system. |
| Rail Deflection | Minimize the dynamic spread of the rails during operation. I.e., maximize bore stiffness to maintain desired bore geometry for the armature. |
| Durability | The launcher should provide sufficient strength to withstand applied loading at operational temperatures. |
| Cost | Cost of the launcher should be minimized. Cost may explicitly consider the quantity to be fabricated. |

Fiber composite over-wrap housings

With current Army tactical focus on lightweight systems [4], the majority of recent efforts has been applied to fiber composite based over-wrapped railgun housings. This is due to the seemingly reasonable assertion that “the laminated steel construction method appears inappropriate for lightweight barrels [5].” Over-wrapped railgun housings have been investigated and reported by many investigators [6], [7], [5], [8], [9], [10]. A common finding is that it is particularly challenging to control the rail deflection using over-wrapped railgun housings [5], [6]. The low cross-ply stiffness of the composite results in poor radial stress transfer through the thickness of the over-wrap [6]. As a consequence of this poor radial modulus, attempts to increase bore stiffness via thicker composite wraps swiftly reach a point of diminishing return [7]. Because of this, it has been noted that attaining high bore stiffness with an over-wrapped barrel is “extremely difficult [5].” For a given core assembly, an infinitely thick composite wrap may not provide a sufficiently stiff bore to meet stringent specifications.

It has long been known that compressive preload of any sidewall insulator enables the insulator modulus to mitigate bore deflection. Achieving such a desired state in over-wrap housings has known challenges as demonstrated by the Los Alamos HIMASS launchers [11]. A novel over-wrap housing that incorporates a compressive preload of ceramic sidewall insulators using press-fit tapered composite bandings is intriguing [8]. This may be considered an extension of prior efforts to employ hydraulic preload of the over-wrap housing [13]. Nevertheless, pre-stress achieves bore stiffness predominately by engaging the modulus of the sidewall insulator –not the housing. If other factors limit the modulus of satisfactory sidewall insulator materials, bore stiffness will be directly compromised.

Laminated metallic housings

Laminated metallic railguns have been proposed by many investigators as offering the potential to mature to ultimately become fieldable weapon systems [12], [13], [6], [15], [16]. The principle advantage of laminated containments using isotropic materials is high bore stiffness. Relative to other structures amenable to

achieving high stiffness, the weight of laminated metallic construction is considered moderate [17]. Metallic laminates are also amenable to high operating temperatures [13] and may facilitate passive thermal management [15].

The principle disadvantages of metallic housings are often cited as lacking axial strength and high weight relative to more compliant fiber composite over-wrap housings [9], [4]. An additional disadvantage to laminated construction is the labor intensive process and expense of assembling thousands of laminates into a precision launcher [13].

BACKBONE RAILGUN PREMISE

The premise of the basic backbone railgun is that magnetic transparency may be achieved by machining slits along the length of a monolithic conductive containment tube. This is depicted in Fig. 1 for a round bore railgun employing a cylindrical containment housing. Situating the web of the axial backbone along the plane of symmetry between the rails maintains orthogonality between the conductive planer surfaces of the containment housing and the magnetic field. In analogy with assembled laminated containment housings, as the web thickness becomes small, diffusion of the magnetic field within it becomes fast and magnetic transparency is achieved.

The slits may later be filled with a reinforced epoxy, varnished metal laminates, or left exposed to promote heat dissipation. The filling of slits may be exploited to fine-tune launcher straightness. Heating or tensile preload of the backbone housing during filling of the slits will place the backbone and sternum into a state of axial tension, increasing the flexural stiffness of the launcher as explained by Noel and Bauer [18].

The launcher housing may be over-wrapped with a composite jacket to provide increased flexural stiffness. An over-wrap may also be applied to augment rail containment. It should be understood that thin augmenting composite overwraps may efficiently contribute to bore stiffness in a hybrid housing design. It is thick over-wraps that should be avoided due to low radial modulus.

ADVANTAGES

Producibility

It is anticipated that the machining of slits from a monolithic launcher will lend itself to factory automation far more so than assembling a full length launcher from thousands of individual metal laminates. In particular, it should be understood that the precision required of individual laminates is not required of the slits.

The most direct means to produce prototype backbone railguns is by means of slitting saws using methods identical to those employed to slit rails and improve inductance gradient [13]. Relatively crude devices may be fabricated using band saws. Traveling wire electric-discharge machining (EDM), abrasive water jet cutting, and electrochemical machining (ECM) provide alternatives that may become economically desirable with increased production rates. It is worth noting that ECM methods may leverage existing electroplating facilities used in the fabrication of current tank cannons.

It should be understood that a backbone railgun may not afford a producibility advantage relative to traditional laminated railguns until a threshold quantity are to be fabricated.

High Axial and Bore Stiffness

In general, most of the advantages of laminated metallic housings remain with a backbone railgun. The remaining web of the backbone railgun design mitigates in part the limited axial stiffness of laminated guns [17], [9].

50MM ROUND BORE CASE STUDY

Relative to prior laminated railgun designs, the backbone railgun increases the volume of conductor exposed to the transient magnetic fields of railgun launch. Therefore, backbone railguns will have reduced inductance gradient relative to an equivalent laminated design. Per the premise of the backbone railgun, this negative consequence becomes negligible as the backbone becomes thin. An assessment of the impact on inductance gradient using the method of Mallick [19] has been conducted.

The first geometry analyzed was a 50mm round bore railgun per Table II. The ribs were set to a

thickness of 2mm. To be conservative in inductance gradient computations, the slit width was assumed infinitesimal. Finite slit width is anticipated to further reduce degradation in inductance gradient.

Table II. Railgun Case Study Geometry

| Component | ID [mm] | OD [mm] | |
|----------------------|------------|------------|-----------------------|
| Rails | 50 | 76 | 90° Arc Aluminum |
| Insulators | 50 | 76 | 90° Arc Free Space |
| Backing Insulator | 76 | 82 | Free Space |
| Housing | 82 | 152 | Stainless Steel |

Free Space L'

A free space inductance gradient was calculated using the method of Kerrisk [20]. This constitutes an upper bound on L' for any housing.

Laminated Launcher L'

The inductance gradient was computed assuming a simple laminated design with rib thickness of that of the backbone railgun but with no backbone. This constitutes an upper bound on L' for any backbone housing.

Full Backbone L'

The inductance gradient was computed for a variety of backbone web thicknesses. As the backbone web becomes infinitesimal, the computed inductance approaches that of the laminated launcher. As it becomes wider, the degradation of inductance gradient becomes more pronounced.

Raised Backbone L'

It may be appreciated that raising the backbone and lowering the sternum further from the plane of the armature and rails will reduce the magnetic flux density exposure to the conductive web. Therefore, a raised backbone, wherein the slits are extended to remove half of the height of the web, may be anticipated to reduce inductance gradient losses relative to the full backbone design. As in the case of the full backbone, this computation was conducted for a variety of widths.

Closed Backbone L'

Taken to a logical extreme, a housing design that provides slits removed internally from the bore of the housing, but that do not penetrate the outer diameter, provide an interesting design potential. This may be considered an extension of Price et al's prior design [21] that incorporated a monolithic steel cylinder outer containment removed from the rails by a substantial ceramic backer insulator. This arrangement will provide exceptional axial and beam bending performance, but does compromise inductance gradient.

The results of the case study are presented in Fig. 2 for five configurations as described above.

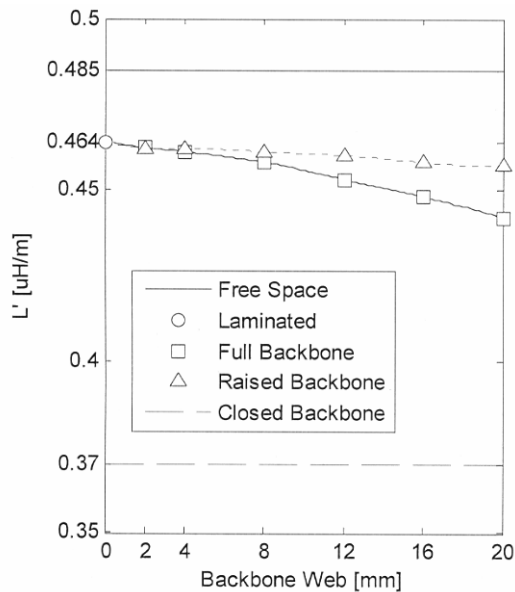


Fig. 2. Computed L' for 50mm Round Backbone Railgun.

40MM MCL SQUARE BORE CASE STUDY

A case study was also made of a square bore backbone railgun based upon the 40mm medium caliber launcher (MCL) as described by Parker and Levinson [1]. The results are presented in Fig. 3.

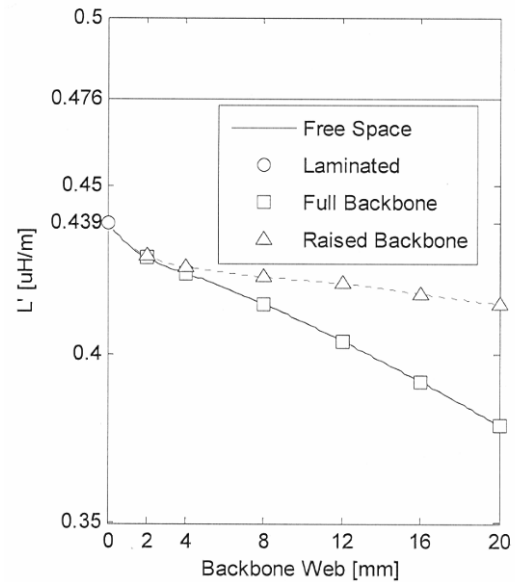


Fig. 3. Computed L' for 40mm MCL Backbone Railgun.

While the parallel between powder gun tube fabrication technology and a round bore backbone railgun configuration may be clear, non-round housings incur self-evident challenges. Clearly, non-round profiles may be broached, in analogy with the method by which large caliber rifling is imparted to powder guns [22]. However, broaching is an expensive operation that is generally applied to remove small volumes of material.

The application of cold rotary forging has been demonstrated as a viable process to impart rifling to gun tubes [23]. The Watervliet Arsenal rotary forge has been used to form rectangular and other non-round components. Net Shape manufacturing using warm and cold forging is an ongoing topic of research with application to cannon manufacture [24]. Fabrication of non-round backbone railgun housings leveraging existing large caliber cannon manufacturing facilities may be viable.

DISCUSSION

The backbone railgun constitutes a different approach to the production of laminated metallic railgun housings. The isentropic nature of metallic housing materials enables thickwalled housings to contribute to bore stiffness. As such, metallic housings reduce traditional reliance upon sidewall insulator preload to leverage insulator modulus for bore stiffness. This provides a level of design freedom to maintain bore stiffness in the absence of insulator preload such as the novel free floating rail configuration of Patch et al [25] or if insulator structure is compromised in configurations amenable to high explosive ammunition. Proposed bore geometries for such multi-purpose ammunition have included trapezoidal [26] and cylindrical [27] scalloping of the sidewall insulators and hexagonal bores [6].

The ultimate tradeoff between weapon needs and requirements for bore stiffness versus launcher weight are not known. Bore stiffness of 0.20% has been achieved using preloaded ceramic sidewall insulators [13] while 2% has been predicted for a 40mm Zylon fiber based over-wrap housing [10]. This provides an order of magnitude range of values that likely include most current opinions of what performance a weapon will ultimately require. If very high stiffness is necessary, metallic containment housings may be weight competitive with alternative solutions –all of which will be heavy relative to lightweight compliant bore launchers.

Neglecting cost, the tradeoff between weight and bore stiffness performance may be optimized using hybrid designs that leverage the radial modulus of a metallic housing to minimize the thickness of applied composite over-wraps. Novel armatures have been proposed to reduce reliance upon bore stiffness to maintain electrical contact [29], [30]. Such endeavors may substantially reduce launcher weight. The converse is also likely true; stiffer and heavier launchers should tend to reduce parasitic armature mass.

CONCLUSIONS

A novel monolithic metallic railgun containment housing has been proposed. The compromise on railgun inductance gradient has been computationally estimated. The analysis verifies that the proposed backbone railgun may provide

inductance gradients comparable to traditional stacked metallic laminate housing designs. The principal rational for the backbone railgun is argued to be achievement of the known thermal and mechanical benefits of metallic railgun housings with a design that may offer producibility advantages.

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REFERENCES

- [1] J. V. Parker and S. Levinson, "Loss of Propulsive Force in Railguns with Laminated Containment," IEEE Trans. Magn., vol. 35, no. 1, pp. 442-446, Jan. 1999.
- [2] D. P. Bauer and D. C. Newman, "High Performance Railgun Barrels for Laboratory Use," IEEE Trans. Magn., vol. 29, no. 1, pp. 362-367, Jan. 1993.
- [3] J. V. Parker, D. T. Berry, and P. T. Snowden, "The IAT Electromagnetic Launch Research Facility," IEEE Trans. Magn., vol. 33, no. 1, pp. 129-133, Jan. 1997.
- [4] M. M. Freeman, "US Army EM Gun Technology Program," Presented at the 12th Electromagnetic Launch Symposium, May 28, 2004.
- [5] M. J. Hinton, A. Howard, N. R. Cooper, D. K. Wallington, and M. A. Firth, "Concepts for Fieldable Electromagnetic Gun Barrels," 10TH U.S. Army Gun Dynamics Symposium Proceedings, ADA404787, pp. 369-384, April 2002.
- [6] G. P. O'Hara and M. Cascio, "Structural Integrity of Metallic Armature Rail Guns," Benét Tech Report ARCCB-TR-87031, ADA188735, Nov. 1987.
- [7] J. Root and A. Littlefield, "Minimizing Rail Deflections in an EM Railgun," paper to be presented at the 13th Symposium on Electromagnetic Launch Technology, Potsdam, Germany, May 2006.
- [8] M. D. Werst, J. R. Kitzmiller, C. S. Hearn, and G. A. Wedeking, "Ultra- Stiff, Low Mass, Electromagnetic Gun Design," IEEE Trans. Magn., vol. 41, no. 1, pp. 262-2265, Jan. 2005.
- [9] J. T. Tzeng, "Structural Mechanics for Electromagnetic Railguns," IEEE Trans. Magn., vol. 41, no. 1, pp. 246-250, Jan. 2005.
- [10] P. Lehmann, M. D. Vo, and W. Wenning, "Comparative Study of Railgun Housings Made of Modern Fiber Wound Materials, Ceramic, or Insulated Steel Plates," IEEE Trans. Magn., vol. 41, no. 1, pp. 200-205, Jan. 2005.
- [11] R. F. Davidson, W. A. Cook, D. A. Rabern, and N. M. Schnurr, "Predicting Bore Deformations and Launcher Stresses in Railguns," IEEE Trans. Magn., vol. 22, no. 6, pp. 1435-1440, Nov. 1986.
- [12] J. J. Hahne, J. H. Herbst, and J. L. Upshaw, "Fabrication and Testing of a 30mm and 90mm Laminated, High L' Railgun Designed and Built at CEM-UT," IEEE Trans. Magn., vol. 31, no. 1, pp. 303-308, Jan. 1995.
- [13] M. D. Werst, K. G. Cook, J. R. Kitzmiller, H. P. Liu, J. H. Price, and H. D. Yun, "Design and Testing of a Rapid Fire, Lightweight, Ultra Stiff Railgun for a Cannon Caliber Electromagnetic Launch System," IEEE Trans. Magn., vol. 31, no. 1, pp. 365-370, Jan. 1995.
- [14] R. L. Laughlin, J. L. Bacon, R. C. Zowarka, and J. H. Price, "Design, Analysis, and Fabrication of Two Lightweight, High L' Railguns," IEEE Trans. Magn., vol. 29, no. 1, pp. 451-456, Jan. 1993.
- [15] J. M. Juston and D. P. Bauer, "A High Performance Railgun Launcher Design," IEEE Trans. Magn., vol. 33, no. 1, pp. 566-570, Jan. 1997.
- [16] E. L. Kathe, M. J. Glennon, M. D. Gully, and K. Olsen, "Integral Containment Electromagnetic Gun," IEEE Trans. Magn., vol. 39, no. 1, pp. 456-461, Jan. 2003.
- [17] S. N. Rosenwasser, "Recent Advances in Large Railgun Structures and Materials Technology," IEEE Trans. Magn., vol. 27, no. 1, pp. 444- 451, Jan. 1991.

- [18] A. P. Noel and D. P. Bauer, "Laminated Barrel Axial Stiffness Assessment," IEEE Trans. Magn., vol. 37, no. 1, pp. 454-456, Jan. 2001.
- [19] J. Mallick, To Be Presented, 13th Electromagnetic Launch Symposium, Berlin, May 2006.
- [20] J. F. Kerrisk, "Current Distribution and Inductance Calculations for Rail-Gun Conductors," Los Alamos National Laboratory Report LA- 9092-MS, November 1981.
- [21] J. H. Price, E. P. Fahrenthold, C. W. G. Fulcher, D. R. Peterson, W. F. Weldon, and R. C. Zowarka, Jr., "Design and Testing of Large-Bore, Ultra-Stiff Railguns," IEEE Trans. Magn., vol. 25, no. 1, pp. 460-466, Jan. 1989.
- [22] D. F. Allsop, "Cannons," Brassey's, London, 1995.
- [23] A. Campione, L. Liuzzi, and F. Heiser, "Cold Rotary Forging," Benét Technical Report WVT-TR-75054, ADA018990, Sep. 1975.
- [24] J. P. Domblesky, R. Shivpuri, and T. Altan, "A Review of Radial Forging Technology Including Preform Design for Process Optimization," Benét Contractor Report, ARCCB-CR-94004, ADA278770, Feb. 1994.
- [25] L. Patch, J. M. Comstock, Y. C. Thio, F. J. Young, "Railgun Barrel Design and Analysis," IEEE Trans. Magn., vol. 20, no. 2, pp. 360-363, Mar. 1984.
- [26] A. E. Zielinski and J. Newill, "A High-Explosive Round for a Rectangular Railgun," IEEE Trans. Mag., vol. 39, no. 1, pp. 319-322, Jan. 2003.
- [27] M. Luciano, "Development and Testing of HE Projectiles for EM Gun –STO," NDIA Guns-Ammo-Rockets-Missiles Conference, New Orleans, LA, 28 Apr 2005.
- [28] M. D. Werst, K. G. Cook, J. R. Kitzmiller, H. P. Liu, J. H. Price, and H. D. Yun, "Design and Testing of a Rapid Fire, Lightweight, Ultra Stiff Railgun for a Cannon Caliber Electromagnetic Launcher System, IEEE Trans. Magn., vol. 31, no. 1, pp. 365-370, Jan. 1995.
- [29] D. J. Hildenbrand, B. Long, J. Rapka, N. Colon, J. Nestor, E. Andricopoulos, and G. Colombo, "Solid Armature Development Program at the ARDEC Electric Armaments Research Center," IEEE Trans. Magn., vol. 31, no. 1, pp. 156-161, Jan. 1995.
- [30] A. P. Noel, A. Challita, and D. P. Bauer, "A Novel Railgun Launch Package Concept," IEEE Trans. Magn., vol. 37, no. 1, pp. 97-100, Jan. 2001.